

Subaru Spectroscopy of the Gravitational Lens HST 14176+5226: Implications for a Large Cosmological Constant¹

Youichi Ohyama,

Subaru Telescope, National Astronomical Observatory of Japan, 650 N. A'ohoku Place,
University Park, Hilo, HI 96720

Takashi Hamana, Nobunari Kashikawa, Masashi Chiba,

National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

Toshifumi Futamase

Astronomical Institute, Tohoku University, Sendai 980-8578, Japan

Masanori Iye, Koji S. Kawabata

National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

Kentaro Aoki,

Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181-0015, Japan

Toshiyuki Sasaki, George Kosugi, and Tadafumi Takata

Subaru Telescope, National Astronomical Observatory of Japan, 650 N. A'ohoku Place,
University Park, Hilo, HI 96720

ABSTRACT

We present new optical spectroscopy of the lens elliptical galaxy in the “Einstein Cross” lens system HST 14176+5226, using the Faint Object Camera and Spectrograph (FOCAS) of the Subaru telescope. Our spectroscopic observations are aimed at measuring the stellar velocity dispersion of the lens galaxy, located at high redshift of $z_L = 0.81$, as an important component to lens models. We have measured this dispersion to be $230 \pm 14 \text{ km s}^{-1}$ (1σ) inside 0.35 effective radii of the lens, based on the comparison between the observed galaxy spectrum and spectral templates of three G-K giants by means of the Fourier cross-correlation method. To extract the significance of this information on the geometry of the universe which also affects the lensing of the background image, we attempt to fit three different lens models to the available data of the

¹Based on observations made with the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

lens system. Provided that the lens galaxy has the structural and dynamical properties (i.e., its radial density profile, core radius, and velocity anisotropy) similar to those of local elliptical galaxies, we calculate the likelihood function for the simultaneous reproduction of both the observed image splitting and newly measured velocity dispersion of the lens. Although the confidence interval depends rather sensitively on the adopted lens models or their parameters, our experiments suggest the larger likelihood for a larger cosmological constant, Ω_Λ : formal 1σ lower limit on Ω_Λ in the flat universe ranges 0.73 to 0.97, whereas 2σ lower limit is basically unavailable. This method for determining the world model is thus dependent on lens models but is insensitive to other unavoidable ambiguities, such as the dust absorption or the evolutionary effects of galaxies. Exploring spectroscopic observations of more lens galaxies at high redshift may minimize the model uncertainties and thus place a much tighter constraint on Ω_Λ .

Subject headings: cosmology: observations – gravitational lensing — quasars: individual (HST 14176+5226)

1. Introduction

Recent cosmological observations have increased various lines of evidence that the evolution of the universe may be dominated by a nonvanishing, normalized cosmological constant, Ω_Λ ($\equiv \Lambda c^2/3H_0^2$, where H_0 is a Hubble constant). These include the distance determination of high-redshift Type Ia supernovae (SNe) (e.g. Perlmutter et al. 1998), number counts of faint galaxies (Fukugita et al. 1990; Yoshii & Peterson 1995), statistics of gravitationally lensed QSOs (Chiba & Yoshii 1999), and age calibration of the Galactic globular clusters (Chaboyer et al. 1998). Also, recent measurements of small-scale anisotropy in the cosmic microwave background (CMB) radiation suggest the flat geometry of the universe ($\Omega_m + \Omega_\Lambda = 1$, where Ω_m stands for the matter density), which may be reconciled with most of the inflationary universe scenarios (de Bernardis et al. 2000). If this result is combined with the currently favored value of $\Omega_m = 0.2 \sim 0.3$ (Bahcall et al. 1999), then a large Ω_Λ ranging 0.7 to 0.8 is inferred.

Except for the CMB measurements, all of the astronomical observations to determine Ω_Λ suffer from unavoidable ambiguities associated with dust absorption inside and/or outside the observed objects in concern, their evolutionary effects, and selection effects. For instance, the interpretation of the Type Ia SNe results should be modified non-trivially

if their luminosities are affected by dust in their host galaxies or intergalactic medium (Aguirre 1999; Totani & Kobayashi 1999) or if their intrinsic properties at high redshift differ from local counterparts (Riess et al. 1999, but see Aldering et al. 2000). Although continuing efforts to minimize these sources of ambiguities have been progressively made, especially by observing higher-redshift SNe (Riess et al. 2001), it may be equally worth pursuing an alternative, independent methodology for the determination of Ω_Λ , which exempts from the above ambiguities.

In this regard, gravitational lensing may be the most powerful and accurate probe to measure cosmological parameters, because the physics involved in it is gravity only (e.g. Mellier 1999). Among various proposed methods relied on gravitational lensing, an interesting approach was adopted by Im et al. (1997), using the dependence of strong lenses on Ω_Λ (Paczynski & Gorski 1981; Gott et al. 1989). They investigated the mean splitting of the lensed multiple images of a distant QSO, $\langle\Delta\theta\rangle$, in conjunction with the mass of a foreground lens galaxy as deduced from its line-of-sight velocity dispersion, σ . They deduced σ from the observed lens magnitude, lens redshift, and the Faber-Jackson relation after correcting for luminosity evolution of a lens. If the mass distribution of a lens is simply represented by a singular isothermal sphere (SIS) as they adopted, we obtain,

$$\langle\Delta\theta\rangle = 8\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_{ls}}{D_s}, \quad (1)$$

where D_s and D_{ls} denote angular diameter distances to the source and between the lens and source, respectively, both of which depend on lens redshift z_L , source redshift z_S , and cosmological parameters (Ω_m, Ω_Λ). Applying this method to eight lens systems, Im et al. concluded $\Omega_\Lambda = 0.64^{+0.15}_{-0.26}$ (1σ) in the flat universe, and $\Omega_m = 1$ is excluded at the 97 % confidence level.

Im et al.’s procedure is subject to ambiguities in dust absorption (Keeton et al. 1998) and in evolution correction for the lens galaxies. Also, the use of the simple SIS model appears to be too simplified. However, as equation (1) implies, if the information on velocity dispersion of a lens is available from *direct* spectroscopic observation, then the concerned ambiguities of dust absorption and galaxy evolution can be excluded in the determination of Ω_Λ . Furthermore, if a more realistic lens model than SIS is applied and if a desired combination of (z_L, z_S) for the lens system is chosen so as to make the distance ratio D_{ls}/D_s being sensitive to Ω_Λ , then we may be able to place a more reliable limit on Ω_Λ . To highlight the latter point, we plot, in Figure 1, the relation between Ω_m and the predicted σ from equation (1), for the case of $z_L = 0.81$, $z_S = 3.40$, and $\langle\Delta\theta\rangle/2 = 1.''5$ (solid line) approximately corresponding to the lens system HST 14176+5226 employed in this paper, and for the case of $z_L = 0.30$ while other quantities are fixed (dotted line). For each case, the upper and lower lines correspond to $\Omega_\Lambda = 0$ and $\Omega_m + \Omega_\Lambda = 1$, respectively. This plot

clearly demonstrates that the effect of Ω_Λ on $\langle\Delta\theta\rangle$ can be more easily separated from that of the lens mass and/or uncertainties in the mass distribution, if more remote lenses, say at $z_L \sim 1$, are utilized in this analysis. A similar method using Einstein ring systems has been proposed by Futamase and Hamana (1999).

Based on the above motivation, we conducted the direct measurement of velocity dispersion for the lens galaxy of the “Einstein Cross” HST 14176+5226, using the FOCAS (Kashikawa et al. 2000) mounted on the Subaru telescope. This lens system was serendipitously discovered in the WFPC2 images from the *HST* Medium Deep Survey (Ratnatunga et al. 1995; 1999; Knudson et al. 2001). The lensed source appears to be a QSO at $z_S = 3.4$ (Crampton et al. 1996; Moustakas & Davis 1998), splitted into four images in a symmetric configuration. The foreground lens galaxy is a red, remote elliptical galaxy at $z_L = 0.81$, and its bright apparent magnitude (F814W= 19.8, F606W= 21.7) enabled us to obtain adequate spectra of high enough S/N with the 8.2 m telescope. Thus, combined the observational results with the detailed lens modeling, it may be possible to place a useful limit on Ω_Λ .

This paper is organized as follows. In §2, we present the spectroscopic observations and data reduction. Our technique to calibrate the line-of-sight velocity dispersion from the derived spectrum is described in §3. In §4, we describe the lens modeling and stellar dynamics of the lens galaxy. Model fittings to the lens system and the results for the determination of Ω_Λ are presented. In §5, implications of the results and further prospects of the work are discussed.

2. Observations and Data Reduction

Observations were made with the FOCAS attached on the Subaru 8.2 m telescope on 2001 June 18. The seeing condition was $0''.8\text{--}0''.9$ during the observation. We used the narrow $0''.4$ slit along the major axis of the lens galaxy (PA= -41.5°). The narrow slit was selected aiming for higher wavelength resolution for better velocity measurement accuracy. The 300 lines mm^{-1} grating together with a Y47 order-cut filter allowed us to obtain an optical spectrum between 4700\AA and 9000\AA with a pixel resolution of 1.39\AA . The spatial resolution was $0''.4$ per pixel by using 4-pixel on-chip binning. We obtained six 1800 seconds exposures.

After subtracting the bias in a standard manner, flat fielding, the optical distortion corrections, and cosmic ray removal were applied using the dedicated software (Yoshida et al. 2000) for each frame. Wavelength calibration was made based on both the calibration

Th-Ar lamp and the telluric OH lines. The accuracy of the wavelength calibration was measured with OH lines to be $\simeq 0.12\text{\AA}$ in RMS over $5500\text{\AA} - 9000\text{\AA}$. Flux calibration was made with a spectroscopic standard star Wolf 1346 and the atmospheric extinction was corrected by using the standard Mauna-Kea extinction curve with a standard manner using IRAF². The lens galaxy spectra were extracted through a $0''.8$ aperture around the nucleus (a 2-pixel wide aperture around the brightest column) from each frame to yield six 1-dimensional spectra. This aperture corresponds to $2 \times 0.35R_e$, where $R_e (= 0.''13 \pm 0.''05)$ denotes an effective radius of a de Vaucouleurs law for the surface brightness profile (Keeton et al. 1998). Finally they were combined with 3- σ clipping average algorithm to remove the residual cosmic ray features. Following van Dokkum and Franx (1996), the instrumental spectral resolution was measured using several OH lines. For this purpose, the sky spectrum was made following the same procedure as for the galaxy spectrum (i.e., using the same wavelength transformation, the aperture extraction, and the frame combination methods). We selected six narrowest (unblended) OH lines around 7300\AA where our target absorption lines of lens galaxy reside and they were fitted simultaneously with multiple Gaussian components whose line widths were assumed to be identical for all lines. We found the instrumental resolution $5.6 \pm 0.3\text{\AA}$ in full width at half maximum (FWHM).

The spectrum of the lens galaxy of HST 14176+5226 is shown in Figure 2. It shows deep CaII H and K absorption lines (3970\AA and 3932\AA detected at 7120\AA and 7185\AA , respectively) and prominent G band feature (4399\AA detected at 7800\AA), suggesting that major contribution in the observed flux of this spectral region could be attributed to the late type giant stars (late G giant \sim early K giant stars).

3. Velocity Dispersion Measurement

The Fourier cross-correlation method (Tonry & Davis 1979) was used to measure the line-of-sight velocity dispersion of the lens galaxy with the FXCOR task implemented in IRAF. This method compares the stellar spectrum as a template with the observed galaxy spectrum by means of the cross-correlation technique. Because we cannot analyze the stellar population in detail given the smaller wavelength coverage and the limited quality of the spectrum, we assume that a single representative population of stars can reproduce the galaxy spectrum well. Therefore we selected three late type giant stars [HD 83805

²IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

(G8III), HD 8491 (K0III), and HD 94247 (K3III)] as spectral templates. All templates were used in the FXCOR task separately to estimate the σ uncertainties in regard to the uncertainties of types of the template. Detailed properties of the template stars used are given in Table 1. The spectra were taken from the stellar spectra library of the C  ude feed spectral library published in the AAD Volume 7 CD-ROM (Leitherer et al. 1996). They cover 3800-4900   with a wavelength resolution of 1.8   (FWHM), and are suitable in our analysis because the resolution is higher than that of the instrumental resolution at the rest-frame of the lens galaxy (3.1   FWHM) and all the prominent redshifted features detected in the lens galaxy spectrum (such as Ca H+K and G band) are included in the templates.

Since the velocity resolution matching between the galaxy and the template spectra is crucial to obtain proper velocity dispersion (e.g. Falco et al. 1997), convolution with the Gaussian-broadening function was applied to the templates (53 km s⁻¹ resolution at the G band) to make the velocity resolution-matched templates (the rest-frame resolution of the lens galaxy spectrum: 91 ± 5 km s⁻¹). We estimate that the error in the velocity resolution matching would result in the error of the velocity dispersion of 4 km s⁻¹ (1 σ): The solution of the velocity dispersion of the lens galaxy (σ) in the Fourier correlation method is related to the instrumental resolution (τ) as $\sigma^2 = \mu^2 - 2\tau^2$ where μ is the width of the cross correlation peak (Tonry & Davis 1979), and, hence, $\delta\sigma \simeq 2\tau\delta\tau/\sigma \simeq 4$ km s⁻¹ for $\sigma = 230$ km s⁻¹ (see below), $\tau = 91$ km s⁻¹, and $\delta\tau = 5$ km s⁻¹.

Following Falco et al. (1997), we analyzed the velocity dispersion of the lens galaxy in the following ways. First, the spectra were pre-processed to be used in FXCOR. Spectra around 7050  - 8200   for the lens galaxy, or 3900   - 4500   for templates, were selected to include interesting absorption features such as Ca H, K and G band. All spectra were normalized by the continuum which was obtained by fitting the spectra with the low-order polynomial function. In this fitting, strong absorption features such as Ca H and K, G band, and atmospheric A band were excluded. Using these spectra, we measured the redshift of the galaxy as $z = 0.811$ by the FXCOR. Note that the redshift was determined consistently regardless of the stellar templates employed and of the detailed FXCOR parameters due to strong absorption features. Our redshift estimate is almost consistent with Koo et al. (1996, $z = 0.811$) and Crampton et al. (1996, $z = 0.809$). Adopting thus derived redshift of the lens galaxy, we produced the rest-frame lens galaxy spectrum (blue-shifted to $z = 0$) for further line width analysis.

Then we made calibration curves which relate the velocity dispersion (σ) with the FWHM of the cross-correlation function (CCF) peak measured with the FXCOR (see Falco et al. 1997). Resolution-matched templates were convolved with a series of

Gaussian-broadening functions in which the velocity dispersion ranges from 45 km s^{-1} to 270 km s^{-1} . One can obtain the calibration curve by running the FXCOR for various combinations of the resolution-matched templates and the Gaussian-broadened templates. In FXCOR, we used the following parameters to calculate the CCF and to measure the width of its peak. We tried two spectral regions for each template (two out of the following three regions: A: $4250 - 4450 \text{ \AA}$, B: $4250 - 4470 \text{ \AA}$, and C: $4250 - 4500 \text{ \AA}$) in calculating the CCF. The regions were selected to include G band but to exclude the atmospheric A band and Ca H and K lines since the calculation with Ca H and K would give problematic result because of their intrinsically wider line width (Tonry 1998). Apodization of 5% (at each end) was applied on all spectra before the Fourier transformation to minimize the spectral aliasing effects. Lowest wavenumber portion of the Fourier-transformed spectra ($\lesssim 110 \text{ \AA}^{-1}$) were not used to avoid the effect of the continuum variation remaining even after the continuum normalization procedures. After the cross-correlation, the FWHM of the CCF peak were measured by Gaussian profile fitting over either central 30 or 35 lags ($\sim \pm 674$ or $\pm 786 \text{ km s}^{-1}$ from the peak) around the peak. The reason why we used two fitting wavelength regions on spectra and two fitting widths on CCF is to estimate the σ uncertainties in the FXCOR fitting procedure. In this way, we got 12 calibration curves in total (three templates, two wavelength fitting regions per template, and two lag widths per each combination of the templates and the wavelength fitting region).

Next, we ran the FXCOR twelve times with the rest-frame lens galaxy spectrum and the resolution-matched templates to measure the FWHM of the CCF peak. The same parameters of the FXCOR as in making the calibration curves were used in each run. The peaks of the CCFs could be represented well by a Gaussian function like in making calibration curves, and the fittings were made with a typical error of $\simeq 10 \text{ km s}^{-1}$ for all cases. In order to check how well the CCF peak fitting could be made and to know how the noise signal of the observed galaxy spectrum could possibly affect the measurement, thirty artificial noise spectra were made with the mknoise task of the artdata package in IRAF, and were added to the observed galaxy spectrum to increase the root-mean-square noise level by $\sim 20\%$. Then, we ran the FXCOR thirty times with the noise-added spectra for one case of the calibration curve, and found that a scatter of the results is $\simeq 12 \text{ km s}^{-1}$ with the mean value being almost as same as that for the original spectrum within 1 km s^{-1} . Note that, although the scatter is slightly worse than the fitting error for one CCF width measurement with the original spectrum (without artificial noise), the small increase ($\sim 20\%$) is most likely to come from the artificial noise added to the observed spectrum. Considering all these experiments, we adopted a 1σ uncertainty of 10 km s^{-1} in the CCF measurement.

The twelve CCF peak width values obtained with original lens galaxy spectrum for

various parameters were then converted to velocity dispersion by using the corresponding calibration curves. We obtained $\sigma = 217 \sim 244 \text{ km s}^{-1}$ with moderately good Tonry-Davis R values ($R = 12 - 15$) for all FXCOR runs (Table 2). Here the Tonry-Davis R value gives the signal-to-noise ratio of the CCF peak (Tonry and Davis 1979), and is also shown to indicate how well the galaxy and template spectra are correlated with each other. Since σ obtained for each calibration curve are almost similar, we adopt the R -weighted mean σ value of 230 km s^{-1} as a most likely value, and the 1σ uncertainties originating from the choice of different templates, fitting wavelength regions, and CCF fitting widths would be $\sim 8 \text{ km s}^{-1}$ based on the scatter of the derived σ for each FXCOR run. Figure 3 shows the normalized rest-frame lens galaxy spectrum overlaid by the Gaussian-broadened ($\sigma = 230 \text{ km s}^{-1}$) template of HD 83805 (the case of the best R value) as well as the residual spectrum (galaxy spectrum – Gaussian-broadened template). To show how remaining sky spectrum may possibly affect the fitting, we also show below the sky spectrum which is red-shifted by the same amount as for the lens galaxy spectrum. Wavelength region around Ca H and K are also shown although the region was not used in the FXCOR analyses. One may find that the G band profile of the galaxy can be fitted by the Gaussian-broadened template very well, and Ca H and K lines are also represented by the template relatively well. Although there are some remaining features in the residual spectrum such as absorption features at 4000\AA and 4435\AA , they are likely to come from the sky subtraction residual. Therefore, we confirmed that the stellar templates used were indeed suitable for representing the lens galaxy spectrum.

Finally we summarize errors associated with all above procedures (Table 3). First, error in the template-galaxy velocity matching is 4 km s^{-1} (1σ) based on the instrumental resolution uncertainty. The CCF peak width measurement with the velocity-matched spectrum can be made with 10 km s^{-1} accuracy (1σ) for one FXCOR run for a calibration curve whose parameters are spectrum template, wavelength fitting region, and fitting width of the CCF peak. Then, twelve FXCOR runs for twelve calibration curves, all of which seem equally suitable for the FXCOR parameters, give 8 km s^{-1} scatter (1σ) of the velocity dispersion. Assuming all these sources of error are independent of each other, the overall 1σ uncertainty of the velocity dispersion is estimated to be $(4^2 + 10^2 + 8^2)^{0.5} \simeq 14 \text{ km s}^{-1}$.

4. Lens Modeling

4.1. Lens Models

In order to demonstrate what constraints the current velocity measurement of the lens galaxy provides on cosmologies, we investigate lens mass models which reproduce the key

observational information on the lens system (image positions) as a function of cosmological parameters. Our lens models are represented by a cored isothermal ellipsoid (CIE) in an external shear field to take advantage of its simplicity and also generality. A similar lens model to ours, a singular isothermal ellipsoid (Kassiola & Kovner 1993; Kormann et al. 1994), has been known to be broadly consistent with observations of various lens systems (e.g. Keeton et al. 1998). An isothermal profile for the total mass distribution of ellipticals is well supported by the detailed dynamical studies of local ellipticals (Rix et al. 1997; Gerhard et al. 2001), individual lens modeling, and statistics (e.g. Maoz & Rix 1993; Kochanek 1995; Grogin & Narayan 1996). The inclusion of an external shear field appears to be necessary both to improve the fits of lens models to the data and to make an axis ratio distribution of individual lenses being consistent with the observed axis ratio distribution of light (Keeton et al. 1997). We allow a finite central core in the lens models, because recent *HST* photometry for the centers of ellipticals has revealed the presence of a finite core in bright ellipticals (Faber et al. 1997; Ravindranath et al. 2001).

The CIE model is parameterized by an ellipticity of mass distribution ϵ , where the axis ratio is given by $\sqrt{(1 - \epsilon)/(1 + \epsilon)}$, position angle of its semi-major axis ϕ_ϵ , core size r_c , and line-of-sight velocity dispersion σ_{tot} . Given such a lens, the lens equation relates the position of a source (β_1, β_2) on the source plane to the positions of images (θ_1^i, θ_2^i) ($i = 1 \dots 4$ for the four-image case) on the lens plane (where the positions are relative to the lens center),

$$\beta_1 = \theta_1 - \alpha_0 \frac{(1 - \epsilon)\theta_1}{\sqrt{(1 - \epsilon)\theta_1^2 + (1 + \epsilon)\theta_2^2 + \theta_c^2}} - \gamma_1\theta_1 - \gamma_2\theta_2, \quad (2)$$

$$\beta_2 = \theta_2 - \alpha_0 \frac{(1 + \epsilon)\theta_2}{\sqrt{(1 - \epsilon)\theta_1^2 + (1 + \epsilon)\theta_2^2 + \theta_c^2}} - \gamma_2\theta_1 + \gamma_1\theta_2, \quad (3)$$

where θ_c is the angular size of a core ($= r_c/D_l$, where D_l denotes angular diameter distance to the lens) and α_0 characterizes the strength of a lens as defined by $\alpha_0 \equiv 4\pi(\sigma_{tot}/c)^2 D_{ls}/D_s$. The effects of the external shear, which is parameterized by the strength $\gamma = (\gamma_1^2 + \gamma_2^2)^{1/2}$ and orientation $\tan 2\phi_\gamma = \gamma_2/\gamma_1$, are also included in the above equations.

We consider three different lens models. The first is the CIE model without the external shear, which is represented by ten parameters: four for source and lens positions, four for lens parameters, and two for cosmological parameters (Ω_m, Ω_Λ). The second is the CIE model with the external shear (CIE+ES), which introduces additional two parameters, so that the total number of parameters is twelve. The third is similar to the CIE model but the lens coordinates are treated as free parameters (CIE+LP). This takes into account the possible finite difference between the observed galaxy center and the center of the gravitational potential. In this model, we do not consider the external shear, so that the total number of parameters is twelve.

As a part of observational constraints on the models, we adopt the positions of the four lensed images and the lens galaxy. The flux ratios between the optical images are excluded in the fitting procedure, because these are largely affected by dust extinction, microlensing by stellar masses, or dark matter substructure (e.g. Mao & Schneider 1998; Chiba 2002). We refer to *HST* data available on the CASTLES Survey’s web site (<http://cfa-www.harvard.edu/castles/>) for the positions and their uncertainties (0."03) of the current lens system. For the positional uncertainty of the lens galaxy, we adopt a slightly more conservative value (0."05 instead of 0."03) because of the extended nature of the galaxy image, although this change of the positional uncertainty turns out *not* to affect the dependence of the image fitting on the model parameters as performed below.

4.2. Stellar Dynamics

The velocity dispersion, σ_{tot} , as a parameter of the lens model is not a directly observable quantity, while what we have measured as reported in the previous section is the surface-brightness weighted average of the line-of-sight velocity dispersion of a stellar component interior to a projected radius R , hereafter denoted as $\langle \sigma_{los}^2(R) \rangle^{1/2}$ (Kochanek 1993). To relate $\langle \sigma_{los}^2(R) \rangle^{1/2}$ with σ_{tot} , we assume that the total mass density, consisting of a luminous stellar and dark matter component, follows a cored isothermal distribution, to be consistent with our lens model, and that the velocity anisotropy of stars is measured by a parameter β , i.e., $\sigma_\theta^2 = \sigma_\phi^2 = (1 - \beta)\sigma_r^2$ in a spherical geometry, where $(\sigma_r, \sigma_\theta, \sigma_\phi)$ are velocity dispersions along the polar coordinates (r, θ, ϕ) . Then, for a luminous stellar component having the surface brightness $I(R)$ and line-of-sight velocity dispersion $\sigma_{los}(R)$ at a projected radius R , the Jeans equation yields (e.g. Binney & Tremaine 1987),

$$I(R)\sigma_{los}^2(R) = 2 \int_0^\infty dz \left(1 - \beta \frac{R^2}{r^2} \right) r^{-2\beta} \int_r^\infty dr' \frac{\nu(r')GM(r')}{r'^2} r'^{2\beta}, \quad (4)$$

with $r^2 = R^2 + z^2$, where $\nu(r)$ is the volume luminosity density and $M(r)$ is the total mass inside r , given as $M(r) = 2\sigma_{tot}^2 r / G(1 - r_c/r \arctan r/r_c)$ (Krauss & White 1992; Kochanek 1993). After averaging interior to R , we obtain

$$\langle \sigma_{los}^2(R) \rangle = \int_0^R d^2R' I(R') \sigma_{los}^2(R') / \int_0^R d^2R' I(R'). \quad (5)$$

As is evident from equation (4) and (5), $\langle \sigma_{los}^2(R) \rangle$ depends on two parameters, r_c and β , in such a way that $\langle \sigma_{los}^2(R) \rangle$ at a specific radius R increases with increasing β (as demonstrated in Kochanek 1993) or decreasing r_c . To incorporate these properties into our

likelihood analysis described below, we make a linear regression to the relation between $\sigma_{tot}^2/\langle\sigma_{los}^2\rangle$ and r_c for a given R and β ,

$$\sigma_{tot}^2 = \langle\sigma_{los}^2\rangle \left(a \frac{r_c}{R_e} + b \right), \quad (6)$$

where a and b are coefficients and R_e stands for an effective radius of a de Vaucouleurs law for $I(R)$. We note that the linearity in the relation is an excellent approximation over the observed range of r_c , i.e., $0 \leq r_c/R_e \leq 0.05$ (Faber et al. 1997; Ravindranath et al. 2001). In accordance with our observations reported in Section 2, we set $R/R_e = 0.35$. For β , we take advantage of the detailed dynamical studies of local elliptical galaxies (Gerhard et al. 2001). Gerhard et al. (2001) showed, based on their sample of 21 early-type galaxies, that an average β over the range $0.1R_e$ to $1R_e$ is typically $0.1 - 0.3$ (see their Figure 5). In what follows, we adopt $\beta = 0.2 \pm 0.2$ as a fiducial value, which gives $a = 8.05 \pm 2.40$ and $b = 1.07 \pm 0.06$. Also, according to the detailed photometric studies of early-type galaxies with *HST* by Faber et al. (1997) and Ravindranath et al. (2001), there exists a rather tight, linear correlation between the logarithms of a central velocity dispersion and a core size in bright galaxies. Our regression analysis of Faber et al.’s data for cored E/S0 galaxies (excluding NGC 4486B with a double nucleus) yields $\log r_c(h_{0.8}^{-1} \text{ pc}) = 2.62 \log \sigma(\text{km s}^{-1}) - 4.01$, where $h_{0.8} \equiv H_0/80 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a 1σ error in the determination of $\log r_c(\text{pc})$ from this relation is 0.42. Thus, we obtain $r_c = 120_{-74}^{+196} h^{-1} \text{ pc}$ at the measured velocity dispersion of 230 km s^{-1} , where $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In the likelihood analysis described below, we take into account all of the uncertainties in the above quantities [β , r_c , a , b , and R_e in equation (6)] *in a consistent manner* as sources of the uncertainty in the parameter σ_{tot} .

4.3. Likelihood analysis

We perform the maximum likelihood analysis to find the best model parameters for the reproduction of the current lens system HST 14174+5226. On the assumption that the error in $\sigma \equiv \langle\sigma_{los}^2\rangle^{1/2}$ is represented by Gaussian distribution, we calculate the likelihood function,

$$L(\Omega_m, \Omega_\Lambda) = \frac{1}{\sqrt{2\pi}\delta\sigma} \int d\sigma_v \exp \left[-\frac{(\sigma_v - \sigma)^2}{2\delta\sigma} \right] L(\Omega_m, \Omega_\Lambda, \sigma_v), \quad (7)$$

where

$$L(\Omega_m, \Omega_\Lambda, \sigma_v) \propto \exp \left[-\sum_{i=1}^4 \left(\frac{(\theta_1^{i,model} - \theta_1^{i,obs})^2}{2\delta\theta_1^{i,obs2}} + \frac{(\theta_2^{i,model} - \theta_2^{i,obs})^2}{2\delta\theta_2^{i,obs2}} \right) \right]. \quad (8)$$

In the above equations, $\delta\theta^{i,obs}$ ($i = 1 \dots 4$) and $\delta\sigma$ denote the standard errors in the observed image positions and velocity dispersion, respectively. We then maximize $L(\Omega_m, \Omega_\Lambda)$ to find

the best set of cosmological parameters $(\Omega_m, \Omega_\Lambda)$. We note that due to the constraint in equation (6) for σ_{tot} and $\langle \sigma_{los}^2 \rangle^{1/2}$, the number of parameters in the model is 6 for the CIE model and 8 for the CIE+ES and CIE+LP models. Since we shall restrict our analyses to flat ($\Omega_\Lambda = 1 - \Omega_m$) or open world models ($\Omega_\Lambda = 0$), the number of parameters is further reduced to 5 for the CIE model and 7 for the CIE+ES and CIE+LP models.

4.4. Results

Figure 4 shows the best-fit image positions (solid circles) and source position (cross), compared with the observed image positions and galaxy position (open circles), where the radii of the open circles correspond to 1σ observational uncertainties. Table 4 tabulates the list of the best-fit lens parameters and the corresponding minima of χ^2 divided by the number of degrees of freedom, N_{dof} . The best-fit CIE model (Figure 4a) to the observed images yields $\chi_{min}^2/N_{dof} = 161/3$, which is not satisfactory from the statistical point of view. It is worth noting that both the best-fit lens parameters and the value of χ_{min}^2/N_{dof} are similar to those obtained by Keeton et al. (1998) using a singular isothermal ellipsoid or SIS with an external shear. The inclusion of an external shear field (CIE+ES: Figure 4b) does not improve the goodness of the fit significantly: we obtain $\chi_{min}^2/N_{dof} = 121/1$. In contrast to these two cases, the dramatic improvement of the fit is attained if the galaxy center is a free parameter (CIE+LP: Figure 4c), yielding $\chi_{min}^2/N_{dof} = 13/1$, although the predicted lens position (plus in panel c) deviates rather largely from the observed position.

Although none of the three different models considered here are statistically acceptable to reproduce the configuration of the current lens system in a *precise* manner, all models produce a similar mean separation between the four images, which is also similar to the observed image separation; our experiments show that the variation of the mean separation among the models is less than $\sim 0.''1$ at a fixed set of $(\Omega_m, \Omega_\Lambda)$. This in turn suggests that the limits on the geometry of the universe, $(\Omega_m, \Omega_\Lambda)$, are not significantly different in each model. This is more clearly seen in Figure 5, where we plot the likelihood L normalized by its maximum value as a function of Ω_m . In each model, the lower and upper lines show the flat ($\Omega_\Lambda = 1 - \Omega_m$) and open ($\Omega_\Lambda = 0$) universes, respectively. As is evident, each model yields a similar L vs. Ω_m relation, showing a large probability at a small Ω_m for the flat universe, whereas for the open universe, the probability stays below that for the flat universe. The largest probability is attained at $\Omega_m \sim 0$ for all three cases. This may imply that the observed image configuration and the velocity dispersion of the lens system HST 14176+5226 is best reproduced at a large Ω_Λ : formal 1σ lower limit on Ω_Λ in the flat universe is about 0.9 and 2σ lower limit reads 0.26, 0.62, and 0.00 for the CIE, CIE+ES,

and CIE+LP models, respectively (Table 4).

We further investigate the possible systematic effects on our lens models by changing the fiducial model parameters (β, r_c) and also by accounting for an additional lensing source. First, a 1σ shift of the mean β while maintaining the error of ± 0.2 corresponds to the more extremely anisotropic velocity fields with more tangential ($\beta = 0.0 \pm 0.2$) or radial ($\beta = 0.4 \pm 0.2$) motions of stars in the central region of the lens. We note here that the coefficients (a, b) in equation (6) change accordingly, as $(9.01 \pm 2.05, 1.14 \pm 0.05)$ and $(6.98 \pm 2.82, 1.00 \pm 0.07)$, respectively. Although such extreme velocity fields are unlikely among local elliptical galaxies (Gerhard et al. 2001), our experiments suggest that the effect on the determination of the cosmological parameters is not so significant: the change in 1σ lower limit on Ω_Λ amounts to only $+0.10$ and -0.04 for the CIE model with $\beta = 0.0 \pm 0.2$ and $\beta = 0.4 \pm 0.2$, respectively (Table 4). It is also worth noting that 2σ lower limit on Ω_Λ is somewhat sensitive to this systematic effect, yielding no constraint for $\beta = 0.0 \pm 0.2$ and the change of -0.66 for $\beta = 0.4 \pm 0.2$. Second, the decrease of a mean core radius r_c by 1σ [while maintaining the error of ± 0.42 in $\log r_c$ (h^{-1} pc)] yields the increase of lower limit on Ω_Λ by an amount of 0.04 (1σ) and 0.62 (2σ), whereas the 1σ increase of r_c yields no allowable 1σ and 2σ lower limits on Ω_Λ . Third, we consider an additional uniform sheet of lensing matter to the CIE model (CIE+SHEET in Table 4). This approximates the effect of a possible intervening matter on the lens system as provided by a foreground cluster or group of galaxies (e.g., Turner, Ostriker, & Gott 1984), although there exists no evidence for a significant enhancement of galaxies in the *HST* image of HST 14176+5226 (Ratnatunga et al. 1995; 1999; Knudson et al. 2001). The surface density of the sheet is characterized by a fixed convergence, κ_s , in units of the critical surface density for lensing, so that the total number of model parameters while restricting the universe to be flat is five. Taking into account the fact that the lens appears *not* to reside in the central part of a cluster of galaxies and that there is no evidence for arc-like features in the field of view, κ_s is expected to be much below 1. We take 0.1 as a possibly largest limit for κ_s , which approximately corresponds to a central surface density of a rich cluster (Turner, Ostriker, & Gott 1984). It follows that the additional uniform sheet with $\kappa_s = 0.1$ to the CIE model yields the decrease of lower limit on Ω_Λ by an amount of 0.20 (1σ) and no allowable 2σ limit.

Our experiments thus suggest that the systematics in our lens models affect the confidence interval for reproducing the observed image configuration and velocity dispersion of the lens system HST 14176+5226, whereby 1σ lower limit on Ω_Λ for the flat universe ranges 0.73 to 0.97, whereas 2σ lower limit is basically unavailable. Although this is statistically not justified for concluding the presence of a large Ω_Λ , it is worth noting that in whatever models considered here, the larger Ω_Λ yields the larger likelihood for reproducing

the current lens system.

5. Discussion and Concluding Remarks

The current methodology for determining cosmological parameters is quite insensitive to both dust absorption and evolutionary correction in a lens system. The ambiguity associated with the effects of dust absorption, if any, in the lens concerns the current method in only an indirect manner, through the calibrations of, e.g., the galaxy center, effective radius, and surface-brightness weighted average of σ_{los}^2 , where all of the associated errors are expected to be trivial or well within uncertainties of mass models. Also, since we have not utilized the lens magnitude in deriving the velocity dispersion of the lens, our analysis exempts from the ambiguity associated with the luminosity evolution of the lens galaxy, unlike Im et al. (1997). We suspect that the ambiguity involved in utilizing the photometric data is rather significant due to the following considerations. We adopt the Poggianti (1997) work for k -corrections and her E and E2 models for evolution of ellipticals with a current age of 15 Gyr, where e-folding times for star formation rate are 1 Gyr and 1.4 Gyr, respectively. Then, the available photometric data ($V = 21.74$: Ratnatunga et al. 1999, $B - V = 1.4$: Crampton et al. 1996) in conjunction with the Faber-Jackson relation between central velocity dispersion σ and absolute B magnitude M_B , $\sigma = 225 \text{ km s}^{-1} \times 10^{0.1(M_B^* - M_B)}$, where $M_B^* = -19.9 + 5 \log h$ (Im et al. 1997), yield σ of 241 km s^{-1} (E) and 183 km s^{-1} (E2) for the cosmological parameters of $(\Omega_m, \Omega_\Lambda, h) = (1, 0, 0.43)$ (giving the age of the universe of 15 Gyr). Thus, the velocity dispersion derived in this manner is sensitive to galaxy evolution models and its possible range is well beyond the error of the spectroscopic measurements.

We also note that the critical assumption behind our analysis is that the lens galaxy at $z_L = 0.81$ is already in dynamical equilibrium. This appears to be well guaranteed, because various lines of observational evidence, including the analyses of the Mg indices vs. σ relation (Ziegler & Bender 1997; Bernardi et al. 1998) and fundamental plane (van Dokkum et al. 1998) of remote ellipticals, have revealed a much higher redshift for the formation epoch of elliptical galaxies, typically at $z \gtrsim 3$.

The principal source of ambiguities in the current methodology is the variety of possible mass models which equally fit to a lens system. Although the relative significance of this effect is partially diminished by carefully selecting the preferable combination of (z_L, z_S) so as to make the distance ratio D_{ls}/D_s being sensitive to Ω_Λ (as demonstrated in Figure 1), the large variety in mass models remains unavoidable. Within the range of our mass models, 1σ lower limit on Ω_Λ varies about 0.2 and there exists a much larger variation in 2σ lower

limit. Furthermore, we are unable to set a meaningful upper limit on Ω_Λ . Our mass models for the lens of HST 14176+5226 have an isothermal density profile ($\rho \propto r^n$ with $n = 2$), which is *statistically* in good agreement with general properties of field ellipticals (e.g. Rix et al. 1997; Gerhard et al. 2001). Although the deviation from $n = 2$ appears to be small in most ellipticals (Gerhard et al. 2001), the smaller (larger) exponent than 2 yields larger (smaller) Ω_Λ , because the total mass of the lens interior to the location of the background lensed images decreases (increases). Effects of non-spherical mass density and/or luminosity density in stellar dynamics may be most uncertain to quantify, because these have not been fully studied yet (e.g. Keeton et al. 1997). Although a detailed examination of the issue is well beyond the scope of this work, it will be important to explore more extensive modeling of internal dynamics of elliptical galaxies for the application of lensing studies.

HST 14176+5226 is one of the ideal sites for applying the current methodology, mainly because of the high redshift of the lens galaxy. In addition to this lens system, in order to minimize the uncertainties associated with the mass models and/or the individual nature of the galaxy, it is important to measure velocity dispersions for more sample lenses at high redshift, thereby placing a tighter and less uncertain constraint on the world model. We note that the use of Einstein ring systems may significantly improve the accuracy of the lens modeling which brings about a much more severe constraint on Ω_Λ . In this regard, it is worth noting that in the $(\Omega_m, \Omega_\Lambda)$ plane, the current method provides a constraint roughly along the $\Omega_\Lambda \sim \text{const.}$ line in the range $0 \lesssim \Omega_\Lambda \lesssim 1$, i.e. crossing the constraints given by Type Ia results ($\Omega_\Lambda \simeq \Omega_m + \text{const.}$) and by CMB results ($\Omega_\Lambda = -\Omega_m + \text{const.}$). Thus, along with these other cosmological observations, the current method also provides useful information on the combination of $(\Omega_m, \Omega_\Lambda)$. Also, in addition to the value of Ω_Λ itself, further observations of various lens systems can be used to derive a useful constraint on the time variability of Ω_Λ (Futamase & Yoshida 2001; Yamamoto & Futamase 2001) or quintessence (Caldwell et al. 1998), by employing lenses at various redshifts; to reveal time dependence or independence of the cosmological constant or dark energy shall offer a great impact not only on cosmology but also on theoretical physics.

We are grateful to all members of the Subaru Telescope, NAOJ, Japan, for their support of the observations. We are also grateful to many of our colleagues for useful discussion and comments on this work. T.H. thanks G. Börner and M. Bartelmann for the hospitality during his stay at Max-Planck-Institut für Astrophysik where a part of the present work was performed. He also acknowledges support from Research Fellowships of the Japan Society for the Promotion of Science. Numerical computation in the present work was partly carried out at the Yukawa Institute Computer Facility.

REFERENCES

- Aguirre, A. N. 1999, *ApJ*, 525, 583
- Aldering, G., Knop, R., & Nugent, P. 2000, *AJ*, 119, 2110
- Bahcall, N. A., Ostriker, J. P., Perlmutter, S., & Steinhardt, P. J. 1999, *Science*, 284, 1481
- Bernardi, M. et al. 1998, *ApJ*, 508, L143
- Binney, J., & Tremaine, S. 1987, *Galactic Dynamics* (Princeton: Princeton Univ. Press)
- Caldwell, R. R., Dave, R., & Steinhardt, P. J. 1998, *Phys. Rev. Lett.*, 80, 1582
- Chaboyer, B., Demarque, P., Kernan, P. J., & Krauss, L. M. 1998, *ApJ*, 494, 96
- Chiba, M. 2002, *ApJ*, 565, 17
- Chiba, M., & Yoshii, Y. 1999, *ApJ*, 510, 42
- Crampton, D., Le Fèvre, O., Hammer, F., & Lilly, S. J. 1996, *A&A*, 307, L53
- de Bernardis, P. et al. 2000, *Nature*, 404, 955
- Faber, S. M. et al. 1997, *AJ*, 114, 1771
- Falco, E. E., Lehár, J., & Shapiro, I. I. 1997, *AJ*, 113, 540
- Falco, E. E., Shapiro, I. I., Moustakas, L. A., & Davis, M. 1997, *ApJ*, 484, 70
- Fukugita, M., Yamashita, K., Takahara, F., & Yoshii, Y. 1990, *ApJ*, 361, L1
- Futamase, T., & Hamana, T. 1999, *Progr. Theor. Phys.* 102, 1037
- Futamase, T., & Yoshida, S. 2001, *Progr. Theor. Phys.* 105, 887
- Gerhard, O., Kronawitter, A., Saglia, R. P., & Bender, R. 2001, *AJ*, 121, 1936
- Gott, J. R., Park, M.-G., & Lee, H. M. 1989, *ApJ*, 338, 1
- Grogin, N. A., & Narayan, R. 1996, *ApJ*, 464, 92 (erratum 473, 570)
- Im, M., Griffiths, R. E., & Ratnatunga, K. U. 1997, *ApJ*, 475, 457
- Kashikawa, N. et al. 2000, *Proc. SPIE*, 1008, 11
- Kassiola, A., & Kovner, I. 1993, *ApJ*, 417, 450

- Keeton, C. R., Kochanek, C. S., & Seljak, U. 1997, *ApJ*, 482, 604
- Keeton, C. R., Kochanek, C. S., & Falco, E. E. 1998, *ApJ*, 509, 561
- Knudson, A., Ratnatunga, K. U., & Griffiths, R. E. 2001, *AJ*, 122, 103
- Kochanek, C. S. 1993, *ApJ*, 419, 12
- Kochanek, C. S. 1995, *ApJ*, 445, 559
- Koo, D. C., Vogt, N. P., Phillips, A. C., et al. 1996, *ApJ*, 469, 535
- Kormann, R., Schneider, P., & Bartelmann, M. 1994, *A&A*, 284, 285
- Krauss, L. M., & White, M. 1992, *ApJ*, 394, 385
- Leitherer, C. et al. 1996, *PASP*, 108, 996
- Mao, S., & Schneider, P. 1998, *MNRAS*, 295, 587
- Maoz, D., & Rix, H.-W. 1993, *ApJ*, 416, 425
- Mellier, Y. 1999, *ARA&A*, 37, 127
- Moustakas, L. A., & Davis, M. *BAAS*, 192, #07.02
- Paczynski, B. & Gorski, K. 1981, *ApJ*, 248, L101
- Perlmutter, S. et al. 1998, *Nature*, 391, 51
- Poggianti, B. M. 1997, *A&AS*, 122, 399
- Ratnatunga, K. U., Ostrander, E. J., Griffiths, R. E., & Im, M. 1995, *ApJ*, 453, L5
- Ratnatunga, K. U., Griffiths, R. E., & Ostrander, E. J. 1999, *AJ*, 117, 2010
- Ravindranath, S., Ho, L. C., Peng, C. Y., Filippenko, A. V., & Sargent, W. L. W. 2001, *AJ*, 122, 653
- Riess, A. G., Filippenko, A. V., Li, W., & Schmidt, B. P. 1999, *AJ*, 118, 2668
- Riess, A. G. et al. 2001, *ApJ*, 560, 49
- Rix, H.-W., de Zeeuw, P. T., Cretton, N., van der Marel, R. P., & Carollo, C. M. 1997, *ApJ*, 488, 702
- Tonry, J. L. 1998, *ApJ*, 115, 1

- Tonry, J. L., & Davis, M. 1979, AJ, 84, 1511
- Totani, T., & Kobayashi, C. 1999, ApJ, 526, L65
- Turner, E. L., Ostriker, J. P., & Gott, J. R. 1984, ApJ, 284, 1
- van Dokkum, P. G., Franx, M., Kelson, D. D., & Illingworth, G. D. 1998, ApJ, 504, L7
- van Dokkum, P. G., & Franx, M. 1996, MNRAS, 281, 985
- Yamamoto, K., & Futamase, T. 2001, Progr. Theor. Phys. 105, 707
- Yoshida, M., et al. 2000, SPIE, 4009, 240
- Yoshii, Y., & Peterson, B. A. 1995, ApJ, 444, 15
- Ziegler, B. L., & Bender, R. 1997, MNRAS, 291, 527

Table 1: Properties of Stars Used as the Spectral Templates

Star	Type	T_{eff}	$\log g$	[Fe/H]
(1)	(2)	(3)	(4)	(5)
HD 83805	G8III	5038	2.14	−0.06
HD 8491	K0III	4703	2.34	+0.09
HD 94247	K3III	4165	2.30	+0.00

¹Star name

²Spectral type

³Effective temperature (K)

⁴Surface gravity in log

⁵Metal abundance in units of solar metallicity

Table 2. Results of the Fourier Cross-Correlation

Star	Fitting region ^a	CCF fitting width	σ^b (km s ⁻¹)	R^c
HD 83805	A	30	221	14.5
	A	35	230	14.4
	B	30	225	15.4
	B	35	232	15.3
HD 8491	A	30	217	13.7
	A	35	227	13.6
	C	30	227	14.2
	C	35	235	14.2
HD 94247	A	30	233	12.3
	A	35	244	12.2
	C	30	233	12.4
	C	35	243	12.4
R -weighted mean			230 \pm 8	

^aA: 4250 – 4450Å, B: 4250 – 4470Å, and C: 4250 – 4500Å.

^bMeasured velocity dispersion.

^cTonry-Davis R value.

Table 3. Error Sources in Velocity Dispersion Measurement

Category	Uncertainties (1σ)
Velocity matching of spectra ^a	4
CCF fitting error ^b	10
FXCOR parameters ^c	8
Total	14 ^d

^aError in matching the velocity resolution between spectra of templates and that of HST 14176+5226.

^bError in fitting the cross correlation function (CCF) peaks with a Gaussian function.

^cUncertainties in selecting template, wavelength region, and fitting width of the CCF peak within FXCOR task.

^d $(4^2 + 10^2 + 8^2)^{0.5} \simeq 14$

Table 4. Results of Maximum Likelihood Analysis^a

Model	ϵ	ϕ_ϵ ($^\circ$)	γ	ϕ_γ ($^\circ$)	δx^b (arcsec)	δy^c (arcsec)	χ^2_{min}/N_{dof}^d	Ω_m^e
CIE	0.30	43	0 (fixed)	—	0 (fixed)	0 (fixed)	161/3	< 0.74 (< 0.07)
CIE+ES	0.25	18	0.15	42	0 (fixed)	0 (fixed)	121/1	< 0.38 (< 0.04)
CIE+LP	0.28	41	0 (fixed)	—	0.017	0.25	12.7/1	< 1.0 (< 0.08)
CIE ($\beta = 0.0 \pm 0.2$)	0.29	43	0 (fixed)	—	0 (fixed)	0 (fixed)	161/3	— (< 0.17)
CIE ($\beta = 0.4 \pm 0.2$)	0.31	43	0 (fixed)	—	0 (fixed)	0 (fixed)	161/3	< 0.28 (< 0.03)
CIE ($r_c = 46 h^{-1}$ pc)	0.31	47	0 (fixed)	—	0 (fixed)	0 (fixed)	161/3	< 0.12 (< 0.03)
CIE ($r_c = 316 h^{-1}$ pc)	0.29	47	0 (fixed)	—	0 (fixed)	0 (fixed)	161/3	— (—)
CIE+SHEET ^f	0.29	47	0 (fixed)	—	0 (fixed)	0 (fixed)	161/3	— (< 0.27)

^aOur standard choice of the parameters (β, r_c) includes $\beta = 0.2 \pm 0.2$ and $r_c = 120^{+196}_{-74} h^{-1}$ pc.

^bThe difference between the galaxy center and the lens center in RA direction in units of arcsec.

^cThe difference between the galaxy center and the lens center in Dec direction in units of arcsec.

^dMinimum of χ^2 divided by the number of degrees of freedom.

^eUpper limit on Ω_m for the flat universe ($\Omega_m + \Omega_\Lambda = 1$) at 2σ (1σ) confidence level.

^fA uniform mass sheet with a surface density $\kappa_s = 0.1$ is assumed, in addition to the CIE model.

Fig. 1.— Predicted line-of-sight velocity dispersion σ of a lens in the simple SIS approximation (equation 1), as a function of Ω_m . Solid line shows the case of $z_L = 0.81$, $z_S = 3.40$, and $\langle\Delta\theta\rangle/2 = 1.''5$ corresponding to the lens system HST 14176+5226 employed in this paper, whereas dotted line shows the case of $z_L = 0.30$ while other quantities are fixed. For each case, the upper and lower lines correspond to $\Omega_\Lambda = 0$ and $\Omega_m + \Omega_\Lambda = 1$, respectively. The comparison between solid and dotted lines indicates that for given z_S and $\langle\Delta\theta\rangle$, the selection of a lens at higher z_L makes σ being sensitive to the value of Ω_Λ for the flat universe.

Fig. 2.— Spectrum of the lens elliptical galaxy in the “Einstein Cross” system, HST 14176+5226. Several absorption-line features are marked.

Fig. 3.— Normalized rest-frame spectrum of HST 14176+5226 (histogram) overlaid by the normalized template spectrum of HD83805 after convolving with the Gaussian velocity-broadening function of $\sigma = 230 \text{ km s}^{-1}$ (solid line). The residual spectrum (galaxy spectrum – broadened stellar template) is also shown. To show how remaining sky spectrum may possibly affect the fitting, we also show below the sky spectrum which is red-shifted by the same amount as for the galaxy spectrum.

Fig. 4.— The lens configuration of the “Einstein Cross”, HST 14176+5226, compared with the model predictions, (a) CIE, (b) CIE+ES, and (c) CIE+LP. Open circles show the observed image positions and lens galaxy position, where the radii of the circles correspond to 1σ observational uncertainties. The best-fit image positions and source position are given by solid circles and cross, respectively. In panel (c) for CIE+LP, the position of the lens galaxy is a free parameter, shown by a plus.

Fig. 5.— The Likelihood normalized by its maximum value as a function of Ω_m . Solid, dotted, and dashed lines denote the CIE, CIE+LP, and CIE+ES models, respectively. In each model, the lower and upper lines show the flat ($\Omega_\Lambda = 1 - \Omega_m$) and open world models ($\Omega_\Lambda = 0$), respectively.